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Studies on the quasi-static and ultrasonic compression of copper tube filled with polyvinyl chloride (PVC) foam

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ABSTRACT

The present study aims to investigate the elastic-plastic behaviour of ultrasonic assisted compression of copper tube filled with PVC closed-cell foam. A series of quasi-static and ultrasonic compression test of copper tube filled with PVC closed-cell foam were conducted at a constant cross head speed of 30 mm/min on dry surface condition. For quasi-static test, specimen was compressed between two rigid platens using universal testing machine without ultrasonic vibration application. Meanwhile, in order to evaluate the specimen behaviour under the ultrasonic vibration application, specimen was placed between a specifically design double-slotted block horn and a rigid platen. The horn was designed and fabricated prior to the test as a medium to transmit the ultrasonic vibration from the ultrasonic transducer to the working specimen. It was tuned to a frequency of 19.89 kHz in longitudinal mode and provided an average oscillation amplitude at 6 µm on the uppermost surface. Following, the characteristics of load-displacement curves for quasi-static and ultrasonic compression tests were analysed. It was found that the compressive load was significantly reduced at the onset of superimposed ultrasonic vibration during plastic deformation and better deformation profile was obtained compared to the one without the ultrasonic vibration application.

1. Introduction

Multifunctional materials that are lightweight, strong, stiff and tough attracts many engineering disciplines including marine, aircrafts, industrial, wind energy, recreation, road and rail applications. Such material is called polyvinyl chloride (PVC) closed-cell foam which has received attention since 1970s. It provides superior strength to weight ratio which has widely used as core materials in sandwich structures for all composite applications which require damage tolerance and weight saving [1, 2]. However, in order to adjust the needs according to the specific application, PVC is important

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to blend with other polymer materials [3]. This is to enhance the PVC material properties. Therefore, formulations has been refined over the years and the characteristics of PVC closed-cell foams fit the needs of other application as well.

Today, PVC closed-cell foam could be extended to the high frequency cyclic force such as in aircraft structure, high speed machine and gas turbine components. Therefore, this is a requirement to identify the response of this material to this condition. Several studies have been conducted to investigate the properties of PVC closed-cell foam following quasi-static and dynamic conditions in order to determine the material responses [2, 4]. The compressive behavior at low and high strain rate as well as the energy absorption had also been discovered [5, 6]. However, a specific study on the effect of ultrasonic vibration on foam is still limited. The application of ultrasonic vibration was commonly used on the solid metal specimens [7]. Thus, this study will focused on the tube metal specimens as it is the leading choices of the modern applications [8].

Ultrasonic application is subject to the feasibility of the ultrasonic technology for generation and transmission of acoustic energy at the required intensity and frequency. This interesting phenomena that are associated with intense and inaudible acoustics waves have many promising fields of ultrasonic application which involve scientific, engineering, chemical, industrial, biotechnology and medical [9]. Here, ultrasonic was used in high-intensity applications which refer to power ultrasonic to change the physical and chemical properties of the materials or systems to which it is applied. Common operating frequencies for high-power ultrasonic application is range between 20 and 100 kHz [10]. The versatility of ultrasonic has been exemplified by the wide range of applications that emerge for this technology. Many attempts have been made on the effects of ultrasonic vibration on the mechanical properties of solid metal [11, 12]. It was found that by superimposing an alternating stress on a workpiece, it highly affected the process rate and reduced the force needed for deformation of the workpiece [11]. The effectiveness of superimpose ultrasonic vibration during the deformation process was related to the friction condition, process rate, vibration mode, ultrasonic frequency and amplitude, material properties and type of deformation [12].

This study had triggered the developments of ultrasonic vibration on a material other than the normally metal. Hence, this study aims to investigate the elastic-plastic behaviour of ultrasonic assisted compression on copper tube filled with PVC closed-cell foam. It is expected that through in-depth understanding of material response under high cyclic stress provides useful information for copper tube filled with PVC closed-cell foam design, fabrication and application.

2. Methodology

2.1 Finite Element Modelling of Ultrasonic Horn

Prior to the ultrasonic compression test, a specifically design of double-slotted block horn was adapted to enable ultrasonic excitation at a desired frequency of 20 kHz in longitudinal mode. Finite Element (FE) method is extremely powerful and versatile computational tools for solving engineering problems of complicated structures with almost arbitrary loading. Although many significant advances have been made in developing FE packages, results obtained must be accurately examined before they can be used [13]. In this study, FE was used to develop a model of ultrasonic horn. The exact dimension of the horn was made based on the trial and error approach. This was completed by adjusting the horn dimension until it achieves the required frequency and mode shape. Thus, after a careful design consideration has been taken, a successful horn dimension was accomplished that fulfil all the desired requirements. The horn was made of high-grade aluminum with dimension 100x100x100 mm and density of 2712 kg/m3. It was fabricated with a double-slotted through both its width and thickness and simulated in a commercial Finite Element (FE) simulation code, ABAQUS

6.14. The slotting configurations were included in this design to maximize vibration amplitude uniformity at the working space. The complete horn model is shown in Figure 1. It was capable to vibrate in the desired frequency where a clear spectrum of the frequency was measured at 19.89 kHz as shown in Figure 2. This measurement took place on the horn top surface in y-direction or in longitudinal mode.

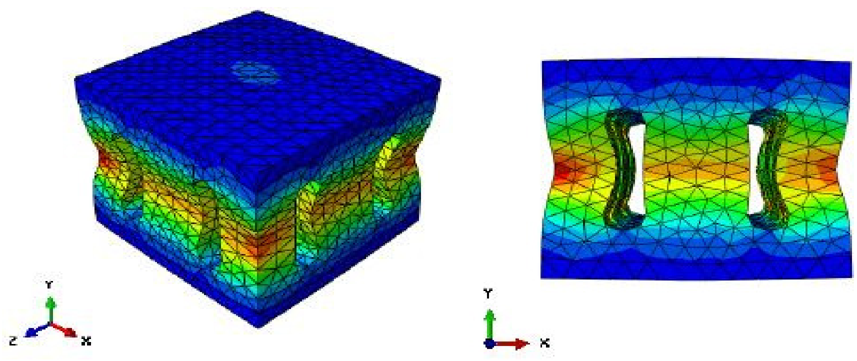

Fig. 1. Longitudinal mode shape diagram

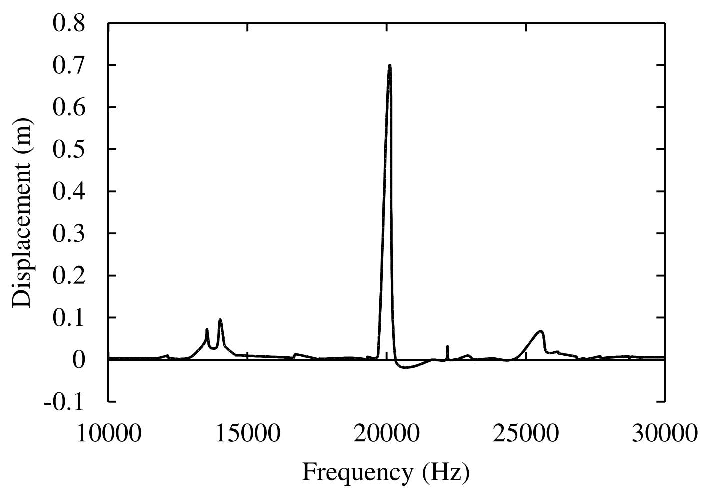

Fig. 2. Frequency response in y-direction

2.2 Material and Testing
2.2.1 Specimen preparation

Cylindrical specimen of copper tube filled with PVC closed-cell foam as shown in Figure 3, were used in the static and ultrasonic compression test. Copper tube with a length of 15 mm and diameter of 9.5 mm were used in the test. Details of the foam's parameter that followed the size of copper tube are given in Table 1.

Table 1
Dimensions of PVC closed-cell foam specimens

Diameter (mm)	Height (mm)	Density, ρ^* (kg/m^3)	Relative density, ρ^* / ρ_s
9.5	15	40	0.02857

ρ_s = 1400 kg/m^3

Fig. 3. Cylindrical specimen

2.2.2 Test set-up

A simple compression test set-up was shown in Figure 4. It was designed to study the effect of ultrasonic vibration application in the static deformation stress of copper tube. The test consists of upper and lower rigid platens. The upper platen was connected to the cross head of the Shimadzu Universal Testing Machine. Meanwhile, the lower rigid platen was used to hold the specimen in the quasi-static compression test. However, in the ultrasonic compression test, the lower rigid platen was replaced by the ultrasonic horn that was designed earlier. The horn will act as a medium to transfer the vibration energy from the ultrasonic transducer which driven by the ultrasonic generator, to the working specimen. The horn was tuned to a longitudinal mode at 19.89 kHz frequency with a uniform nominal vibration peak amplitude of 6 μm on the horn surface. Load-displacement distribution for quasi-static and ultrasonic compression tests were analysed.

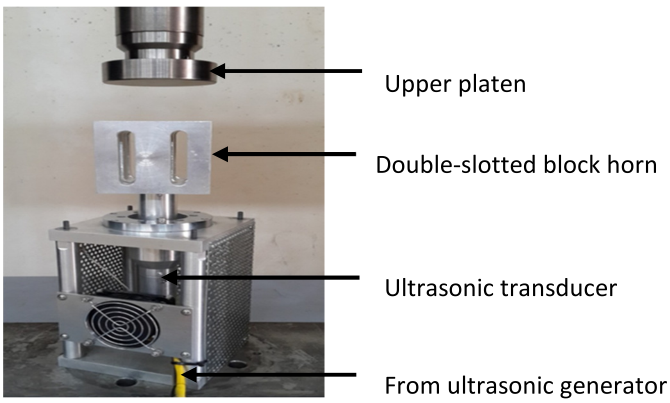

Fig. 4. Ultrasonic compression test set-up

2.2.3 Test Procedures

Quasi-static compression

A series of static compression test of PVC closed-cell foam was conducted at a constant cross head speed of 30 mm/min on dry surface condition. Normal procedure for the quasi-static compression test was conducted where the specimens was statically compressed between two rigid platens.

Ultrasonic compression

The test procedure was then repeated for the ultrasonic compression test, but the lower rigid platen was replaced with a double-slotted block horn. Two sets of ultrasonic compression test were conducted. For the first set, the ultrasonic vibration was applied during post-yield for three short intervals by switching on the ultrasonic generator for duration of 1 second. Successively, when the ultrasonic vibration was discontinued, static compression was continued between these intervals. For the second set, the ultrasonic excitation was applied continuously from the onset of plastic deformation to the completion of the test. Both quasi-static and ultrasonic compression test specimens were stopped until the specimens reduced for more than 50% of its original length. Load-displacement data were recorded through hardware and software of the universal testing machine.

3. Results and discussion

3.1 Characteristics of Load-displacement Curves

To study the effect of ultrasonic vibration during compression test on copper tube filled with PVC foam, set of load-displacement curves has been plotted. The investigation was discussed into three separate compression test according to quasi-static, intermittent ultrasonic and continuous ultrasonic condition of specimens with diameter size of 9.5 mm. This can be understood by referring to Figure 5. For quasi-static compression test, specimens was elastically deformed until it reached a yield point (formation of first folding) at a maximum load value, 1847 N and displacement, 1.08 mm. Thereafter, specimen's deformation involves the formation of progressive folds. The formation of these folds causes the fluctuation in the load until it rises steeply at 8.83 mm of displacement.

Meanwhile, for intermittent ultrasonic compression test, specimens was elastically deformed until it reached a yield point (formation of first folding) at a maximum load value, 1715 N and displacement, 1.28 mm. However, a significant load reduction has been recorded when ultrasonic vibration applied at this point. The compressive load dropped drastically immediate after yield and the load started to regain but at a lower point than the yield point when ultrasonic vibration is removed. Subsequently, the ultrasonic vibration was applied intermittently, providing the load was repetitively dropped and regained at different level before the load increase rapidly at 10.07 mm of displacement.

Next, significant load reduction after yield was recorded for continuous ultrasonic compression. Here, specimens was elastically deformed until it reached a yield point (formation of first folding) at a maximum load value, 1902 N and displacement, 2.04 mm. Later, with the presence of ultrasonic vibration after yield point until the completion of the test, the load dropped drastically and remain at low load values across the displacement until the load rises steeply after it displaced at 9.62 mm.

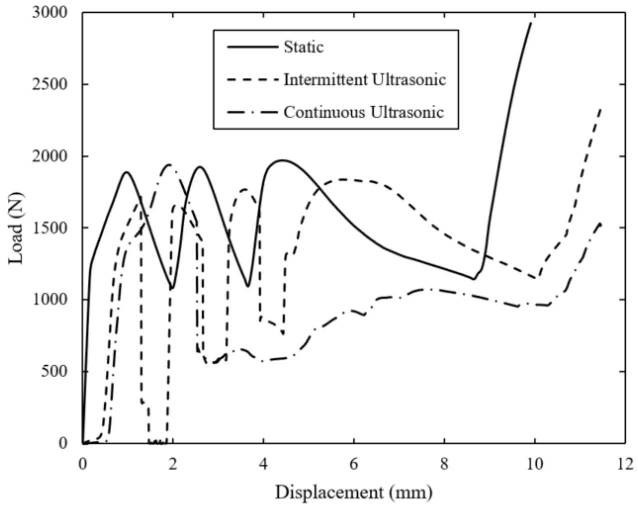

Fig. 5. Load-displacement curves for quasi-static and ultrasonic compression of copper tube filled with PVC closed-cell foam

Based on the comparison of quasi-static and ultrasonic compression test, it can be suggested that the application of ultrasonic vibration in compression test has assisted the deformation process by reducing the compressive load. It was the timing when the ultrasonic excitation was imposed could influence the amount of the load reduction. This could be explained when ultrasonic vibration applied during the weakest point of the compressed tube foam, where further load drop was definitely obtained due to these combined effects. The comparison was also supported by the previous researchers [14-16] who claimed that the load deformation can be remarkably reduced by superimposing ultrasonic vibration on the static load in compression test. A possible explanation was also deducted by Winsper and Sansome [17] who suggested that the load reduction can be associated with the material softening. One of the mechanism that contribute to the load reduction is the friction vector effect [18]. This occurred when the oscillatory velocity of the lower platen exceeds the specimen velocity. Friction vector is a result of the relative motion between the lower platen and specimen which normally acts in perpendicular direction to the specimen motion. But the friction vector is reversed when the lower platen is vibrated. This is because the motion of the lower platen is parallel to the specimen motion, such that it assists the motion to the specimen in the working direction and therefore reduced the friction force then compressive load.

3.2 Deformation Profile

This section was discussed based on the Figure 5 and 6 concurrently. Figure 6 (a) depicts the deformation profile of copper tube that formed three non-symmetric folding following the three separated regions of the fluctuation load as referred to the load-displacement curves for quasi-static compression test. Next, Figure 6 (b) represents the deformation profile for intermittent ultrasonic compression test. It was observed that the specimens obtained more uniform deformation profile compared to the one in quasi-static compression test. Similar to the quasi-static compression test, a load-displacement curve for intermittent ultrasonic compression test that designated into three separated regions of fluctuation load, following the three symmetric folding. On the other hand, a unique folding was observed in the deformation profile of continuous ultrasonic compression test. It was observed that the low load values across the specimen's displacement contribute to the smooth formation of folding.

Fig. 6. Deformation profile of copper tube filled with PVC closed-cell foam for (a) quasi-static, (b) intermittent ultrasonic and (c) continuous ultrasonic compression test

4. Conclusion

Based on the comparison of quasi-static and ultrasonic compression test of copper tube filled with PVC foam, it can be suggested that significant load reduction was observed when the ultrasonic vibration was applied. Thus, the results showed that the application of ultrasonic vibration on the metal tube filled with foam, also contribute in the reduction of compressive load and better deformation profile was obtained compared to the one in quasi-static compression test.

Acknowledgement
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